

A Very Common Fallacy in Quantum Mechanics: Superposition, Delayed Choice, Quantum Erasers, Retrocausality, and All That

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Abstract

There is a very common fallacy, here called the *separation fallacy*, that is involved in the interpretation of quantum experiments involving a certain type of separation such as the: double-slit experiments, which-way interferometer experiments, polarization analyzer experiments, Stern-Gerlach experiments, and quantum eraser experiments. It is the separation fallacy that leads not only to flawed textbook accounts of these experiments but to flawed inferences about retrocausality in the context of "delayed choice" versions of separation experiments.

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1 Introduction: Separation Fallacy

There is a very common fallacy, here called the *separation fallacy*, that is involved in the interpretation of quantum experiments involving a certain type of separation such as the:

- double-slit experiments,
- which-way interferometer experiments,

- polarization analyzer experiments,
- Stern-Gerlach experiments, and
- quantum eraser experiments.

In each case, given an incoming quantum particle, the apparatus creates a certain labelled or tagged (i.e., entangled) superposition of certain eigenstates (the "separation"). Detectors can be placed in certain positions (determined by the tags) so that when the evolving superposition state is finally projected or collapsed by the detectors, then only one of the eigenstates can register at each detector. The *separation fallacy* mistakes the creation of a tagged or entangled superposition for a measurement. Thus it treats the particle as if it had already been projected or collapsed to an eigenstate at the separation apparatus rather than at the later detectors. But if the detectors were suddenly removed while the particle was in the apparatus, then the superposition would continue to evolve and have distinctive effects (e.g., interference patterns in the two-slit experiment).

Hence the separation fallacy makes it *seem* that by the delayed choice to insert or remove the appropriately positioned detectors, one can *retro-cause* either a collapse to an eigenstate or not at the particle's entrance into the separation apparatus.

The separation fallacy is remedied by:

- taking superposition seriously, i.e., by seeing that the separation apparatus created an entangled *superposition* state of the alternatives (regardless of what happens later) which evolves until a measurement is taken, and
- taking into account the role of detector placement ("contextuality"), i.e., by seeing that if a suitably positioned detector, as determined by the positional labels or tags, can only detect one collapsed eigenstate, then it does not mean that the particle was *already* in that eigenstate prior to the measurement (e.g., it does not mean that the particle "went through one slit," "took one arm," or was already in a polarization or spin eigenstate).

The separation fallacy will be first illustrated in a non-technical manner for the first four experiments. Then the lessons will be applied in a slightly more technical discussion of quantum eraser experiments—where, due to the separation fallacy, incorrect inferences about retrocausality have been rampant.

2 Double-slit experiments

In the well-known setup for the double-slit experiment, if a detector D_1 is placed a small finite distance after slit 1 so a particle "going through the other slit" cannot reach the detector, then a hit at the detector is usually interpreted as "the particle went through slit 1."

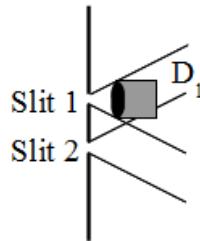


Figure 1a

But this is incorrect. The particle is in a superposition state, which we might represent schematically as $|Slit1\rangle + |Slit2\rangle$, that evolves until it hits the detector which projects (or collapses) the

superposition to one of (the evolved versions of) the slit-eigenstates. The particle's state was not collapsed earlier so it was not previously in the $|Slit1\rangle$ eigenstate, i.e., it did not "go through slit 1."

Thus what is called "detecting which slit the particle went through" is a misinterpretation. It is only placing a detector in such a position so that when the superposition projects to an eigenstate, only one of the eigenstates can register in that detector. It is about *detector placement*; it is not about which-slit.

By erroneously talking about the detector "showing the particle went through slit 1," we imply a type of retro-causality. If the detector is suddenly removed after the particle has passed the slits, then the superposition state continues to evolve and shows interference on the far wall (not shown)—in which case people say "the particle went through both slits." Thus the "bad talk" makes it seem that by removing or inserting the detector after the particle is beyond the slits, one can retro-cause the particle to go through both slits or one slit only.

This sudden removal or insertion of detectors that can only detect one of the slit-eigenstates is a version of Wheeler's delayed choice thought-experiment [10].

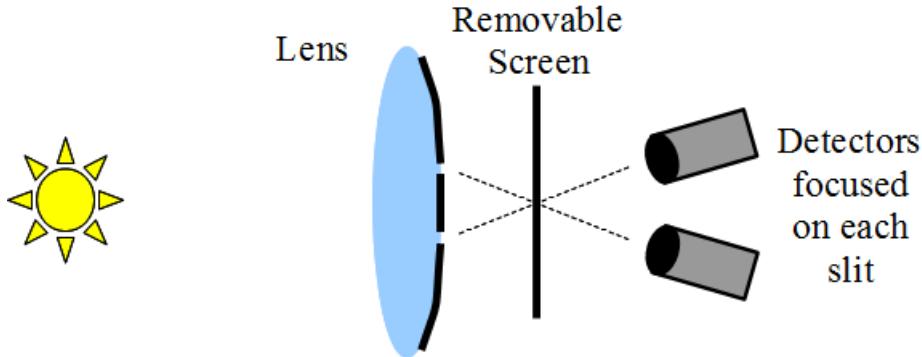


Figure 1b. Wheeler's Delayed Choice 2 Slit Experiment

In Wheeler's version of the experiment, there are two detectors which are positioned behind the removable screen so they can only detect one of the projected (evolved) slit eigenstates when the screen is removed. The choice to remove the screen or not is delayed until after a photon has traversed the two slits.

"In the one case [screen in place] the quantum will ... contribute to the record of a two-slit interference fringe. In the other case [screen removed] one of the two counters will go off and signal in which beam—and therefore from which slit—the photon has arrived." [10, p. 13]

The separation fallacy is involved when Wheeler infers from the fact that one of the specially-placed detectors went off that the photon had come from one of the slits—as if there had been a projection to one of the slit eigenstates at the slits rather than later at the detectors.

Such descriptions using the separation fallacy are unfortunately common and have generated a spate of speculations about retrocausality.

3 Which-way interferometer experiments

Consider a Mach-Zehnder-style interferometer with only one beam-splitter (e.g., half-silvered mirror) at the photon source which creates the photon superposition: $|T1\rangle + |R1\rangle$ (which stand for "Transmit" to the upper arm or "Reflect" into the lower arm at the first beam-splitter).

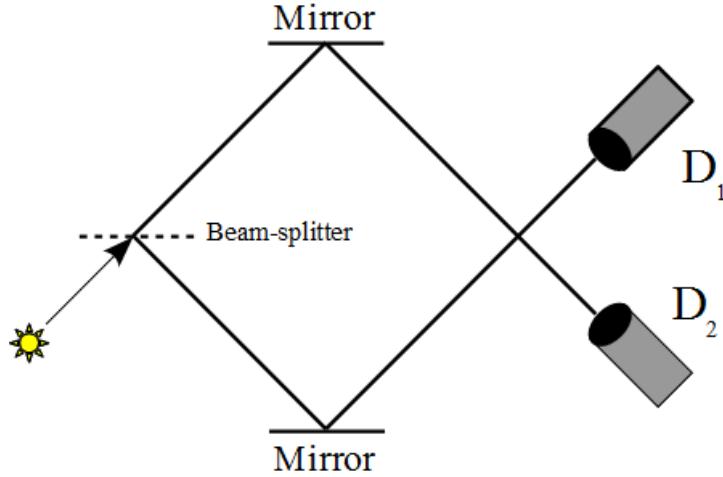


Figure 2: One beam-splitter

When detector D_1 registers a hit, it is said that "the photon was reflected and thus took the lower arm" of the interferometer and similarly for D_2 and passing through into the upper arm. This is the interferometer analogue of putting two up-close detectors after the two slits in the two-slit experiment.

And this standard description is incorrect for the same reasons. The photon stays in the superposition state until the detectors force a projection to one of the (evolved) eigenstates. If the projection is to the evolved $|R1\rangle$ eigenstate then only D_1 will get a hit, and similarly for D_2 and the evolved version of $|T1\rangle$. The point is that the placement of the detectors (like in the double-slit experiment) only captures one or the other of the projected eigenstates.

Now insert a second beam-splitter as in the following diagram.

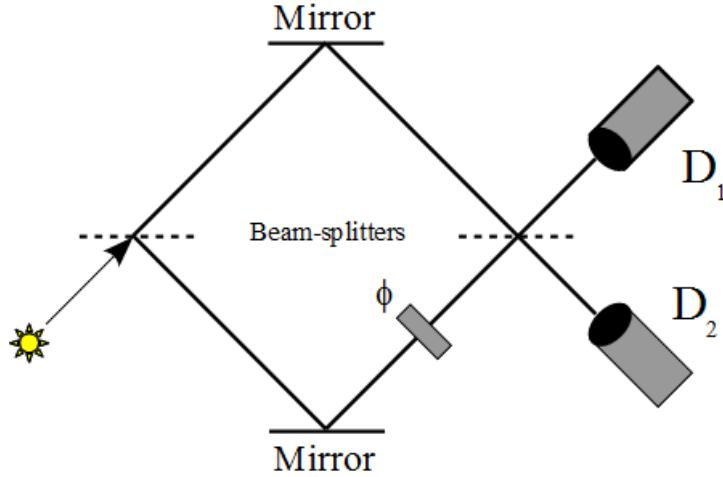


Figure 3: Two beam-splitters

It is said that the second beam-splitter "erases" the "which-way information" so that a hit at either detector could have come from either arm, and thus an interference pattern emerges.

But this is also incorrect. The superposition state $|T1\rangle + |R1\rangle$ (which contains no which-way information) is further transformed at the second beam-splitter to the superposition $|T1, T2\rangle + |T1, R2\rangle + |R1, T2\rangle + |R1, R2\rangle$ that can be regrouped according to what can register at each detector:

$$[|T1, R2\rangle + |R1, T2\rangle]_{D_1} + [|T1, T2\rangle + |R1, R2\rangle]_{D_2}.$$

The so-called "which-way information" was not there to be "erased" since the particle did not take one way or the other in the first place. The second beam-splitter only allows the superposition state $[|T1, R2\rangle + |R1, T2\rangle]_{D_1}$ to be registered at D_1 or the superposition state $[|T1, T2\rangle + |R1, R2\rangle]_{D_2}$ to be registered at D_2 . By using a phase shifter ϕ , an interference pattern can be recorded at each detector since each one is now detecting a superposition that will involve interference.

By inserting or removing the second beam-splitter after the particle has traversed the first beam-splitter (as in [10]), the separation fallacy makes it seem that we can retro-cause the particle to go through both arms or only one arm.

The point is not the second beam-splitter but the detectors being able to register the collapse to either eigenstate and thus the interference between them. Instead of inserting the second beam-splitter, we could rig up more mirrors, a lens, and a single detector so that when the single detector causes the collapse, then it will register either arm-eigenstate.

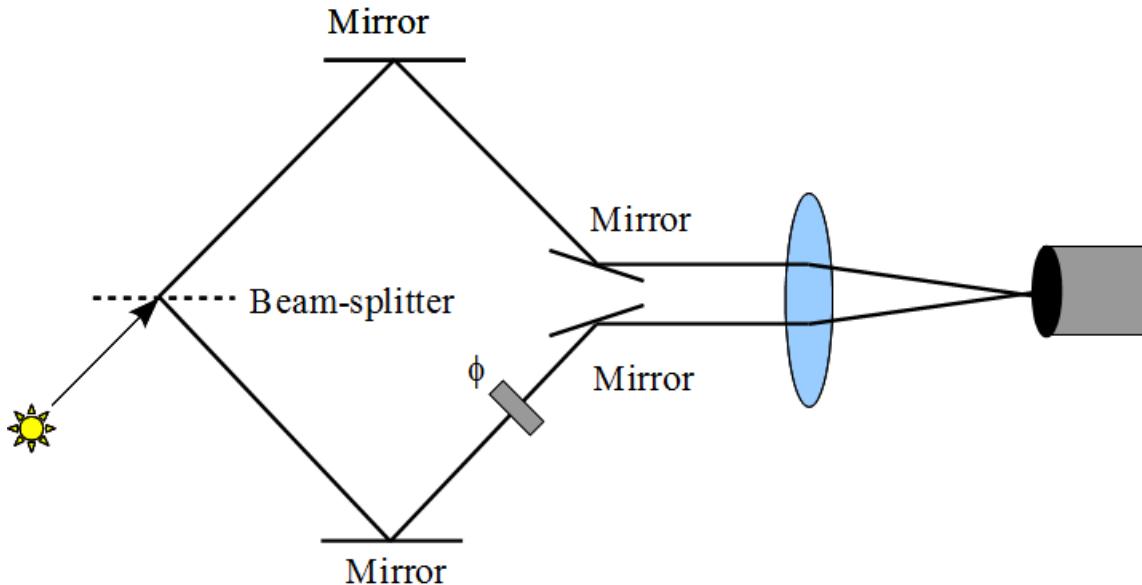


Figure 4: Detector placed to register all hits

This might also be (mis)interpreted as "erasing" the "which-way information" but in fact the photon did not go through just one arm so there was no such information to be erased. The point is the positioning of the detector so that it detects the evolved superposition $|T1\rangle + |R1\rangle$ that will show interference. Any setup that would allow a detector to register both collapsed eigenstates (and thus to register the interference effects of the evolving superposition) would *ipso facto* be a setup that could be (mis)interpreted as "erasing" the "which-way information." That is why the separation fallacy is so persistent in the interpretation of which-way interferometer and other quantum separation experiments.

4 Polarization analyzers and loops

Another common textbook example of the separation fallacy is the treatment of polarization analyzers such as calcite crystals that are said to create two orthogonally polarized beams in the upper and lower channels, say $|v\rangle$ and $|h\rangle$ from an arbitrary incident beam.

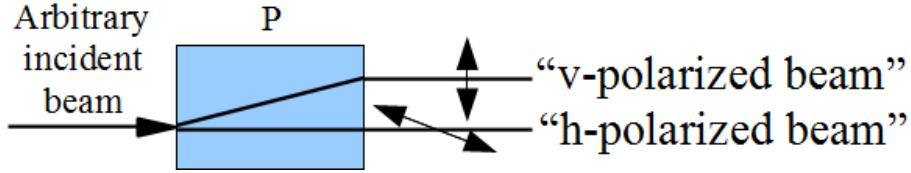


Figure 5: *vh*-analyzer

The output from the analyzer P is routinely described as a "vertically polarized" beam and "horizontally polarized" beam as if the analyzer was itself a measurement that collapsed or projected the incident beam to either of those polarization eigenstates. This *seems* to follow because if one positions a detector in the upper beam then only vertically polarized photons are observed and similarly for the lower beam and horizontally polarized photons. A blocking mask in one of the beams has the same effect as a detector to project the photons to eigenstates. If a blocking mask is inserted in the lower beam, then only vertically polarized photons will be found in the upper beam, and vice-versa.

But here again, the story is about detector (or blocking mask) placement ("placement" is more precise than "contextuality"); it is not about the analyzer supposedly projecting a photon into one or the other of the eigenstates. The analyzer puts the incident photons into a superposition state, an entangled superposition state that associates polarization and the spatial channel. If a detector is placed in, say, the upper channel, then *that* is the measurement that collapses the evolved superposition state. If the collapse is to the vertical polarization eigenstate then it will register only in the upper detector and similarly for a collapse to the horizontal polarization eigenstate for any detector placed in the lower channel. Thus it is misleadingly said that the upper beam was already vertically polarized and the lower beam was already horizontally polarized as if the analyzer had already done the projection to one of the eigenstates.

If the analyzer had in fact induced a collapse to the eigenstates, then any prior polarization of the incident beam would be lost. Hence assume that the incident beam was prepared in a specific polarization of, say, $|45^\circ\rangle$ half-way between the states of vertical and horizontal polarization. Then follow the *vh*-analyzer P with its inverse P^{-1} to form an analyzer loop [3].

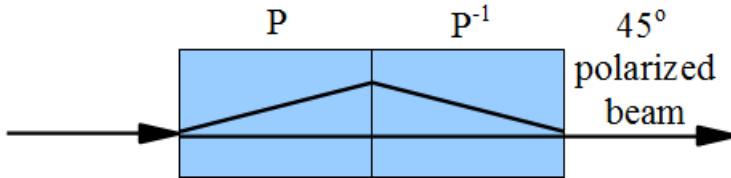


Figure 6: *vh*-analyzer loop

The characteristic feature of an analyzer loop is that it outputs the same polarization, in this case $|45^\circ\rangle$, as the incident beam. This would be impossible if the P analyzer had in fact rendered all the photons into a vertical or horizontal eigenstate thereby destroying the information about the polarization of the incident beam. But since no collapsing measurement was in fact made in P or its inverse, the original beam can be the output of an analyzer loop.

Very few textbooks realize there is even a problem with presenting a polarization analyzer such as a calcite crystal as creating two beams with orthogonal eigenstate polarizations—rather than creating a tagged superposition state so that appropriately positioned detectors can detect only one eigenstate when the detectors cause the projections to eigenstates.

One (partial) exception is Dicke and Wittke's text [1]. At first they present polarization analyzers as if they measured polarization and thus "destroyed completely any information that we had about the polarization" [1, p. 118] of the incident beam. But then they note a problem:

"The equipment [polarization analyzers] has been described in terms of devices which measure the polarization of a photon. Strictly speaking, this is not quite accurate." [1, p. 118]

They then go on to consider the inverse analyzer P^{-1} which combined with P will form an analyzer loop that just transmits the incident photon unchanged.

They have some trouble squaring this with their prior statement about the P analyzer destroying the polarization of the incident beam but they, unlike most texts, struggle with getting it right.

"Stating it another way, although [when considered by itself] the polarization P completely destroyed the previous polarization Q [of the incident beam], making it impossible to predict the result of the outcome of a subsequent measurement of Q , in [the analyzer loop] the disturbance of the polarization which was effected by the box P is seen to be revocable: if the box P is combined with another box of the right type, the combination can be such as to leave the polarization Q unaffected." [1, p. 119]

They then go on to correctly note that the polarization analyzer P did not in fact project the incident photons into polarization eigenstates.

"However, it should be noted that in this particular case [sic!], the first box P in [the first half of the analyzer loop] did not really measure the polarization of the photon: no determination was made of the channel ... which the photon followed in leaving the box P ." [1, p. 119]

There is some classical imagery (like Schrödinger's cat running around one side or the other side of a tree) that is sometimes used to illustrate quantum separation experiments when in fact it only illustrates how classical imagery can be misleading. Suppose an interstate highway separates at a city into both northern and southern bypass routes—like the two channels in a polarization analyzer loop. One can observe the bypass routes while a car is in transit and find that it is in one bypass route or another. But after the car transits whichever bypass it took without being observed and rejoins the undivided interstate, then it is said that the which-way information is erased so an observation cannot elicit that information.

This is not a correct description of the corresponding quantum separation experiment since the classical imagery does not contemplate superposition states. The particle-as-car is in a tagged superposition of the two routes until an observation (e.g., a detector or "road block") collapses the superposition to one eigenstate or the other. Correct descriptions of quantum separation experiments require taking superposition seriously—so classical imagery should only be used *cum grano salis*.

This analysis might be rendered in a more technical but highly schematic way. The photons in the incident beam have a particular polarization $|\psi\rangle$ such as $|45^\circ\rangle$ in the above example. This polarization state can be represented or resolved in terms of the vh -basis as:

$$|\psi\rangle = \langle v|\psi\rangle |v\rangle + \langle h|\psi\rangle |h\rangle.$$

The effect of the vh -analyzer P might be represented as tagging the vertical and horizontal polarization states with the upper and lower (or straight) channels so the vh -analyzer puts an incident photon into the *superposition* state:

$$\langle v|\psi\rangle |v\rangle_U + \langle h|\psi\rangle |h\rangle_L,$$

not into an eigenstate $|v\rangle$ in the upper channel or an eigenstate $|h\rangle$ in the lower channel.

If a blocker or detector were inserted in either channel, then this superposition state would project to one of the eigenstates, and then (as indicated by the tags) only vertically polarized photons would be found in the upper channel and horizontally polarized photons in the lower channel.

The separation fallacy is to describe the *vh*-analyzer *as if* the analyzer's effect by itself was to project an incident photon either into $|v\rangle$ in the upper channel or $|h\rangle$ in the lower channel—instead of only creating the above tagged superposition state. The mistake of describing the unmeasured polarization analyzer as creating two beams of eigenstate polarized photons is analogous to the mistake of describing a particle as going through one slit or the other in the unmeasured-at-slits double-slit experiment—and similarly for the other separation experiments.

It is fallacious to reason that "we know the photons are in one polarization state in one channel and in the orthogonal polarization state in the other channel *because* that is what we find when we measure the channels," just as it is fallacious to reason "the particle has to go through one slit or another (or one arm or another in the interferometer experiment) *because* that is what we find when we measure it." This purely *operational* (or "Copenhagen") description does not take superposition seriously since a superposition state is not "what we find when we measure."

In the analyzer *loop*, no measurement (detector or blocker) is made after the *vh*-analyzer. It is followed by the inverse *vh*-analyzer P^{-1} which has the inverse effect of removing the U and L tags from the superposition state $\langle v|\psi\rangle|v\rangle_U + \langle h|\psi\rangle|h\rangle_L$ so that a photon exits the loop in the untagged superposition state:

$$\langle v|\psi\rangle|v\rangle + \langle h|\psi\rangle|h\rangle = |\psi\rangle.$$

The inverse *vh*-analyzer does not "erase" the which-polarization information since there was no measurement—to reduce the superposition state to eigenstate polarizations in the channels of the analyzer loop—in the first place. The inverse *vh*-analyzer *does erase* the which-channel tags so the original state $\langle v|\psi\rangle|v\rangle + \langle h|\psi\rangle|h\rangle = |\psi\rangle$ is restored (which could be viewed as a type of interference effect, e.g., [3, Sections 7-4, 7-5]).

5 Stern-Gerlach experiment

We have seen the separation fallacy in the standard treatments of the double-slit experiment, which-way interferometer experiments, and in polarization analyzers. In spite of the differences between those separation experiments, there was that common (mis)interpretative theme. Since the "logic" of the polarization analyzers is followed in the Stern-Gerlach experiment (with spin playing the role of polarization), it is not surprising that the same fallacy occurs there.

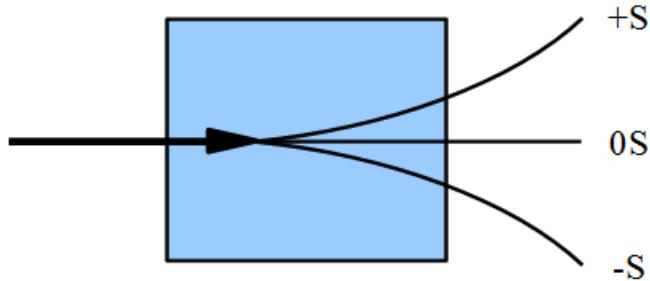


Figure 7: Stern-Gerlach Apparatus

And again, the fallacy is revealed by considering the Stern-Gerlach analogue of an analyzer loop. One of the very few texts to consider such a Stern-Gerlach analyzer loop is *The Feynman Lectures on Physics: Quantum Mechanics (Vol. III)* where it is called a "modified Stern-Gerlach apparatus" [2, p. 5-2].

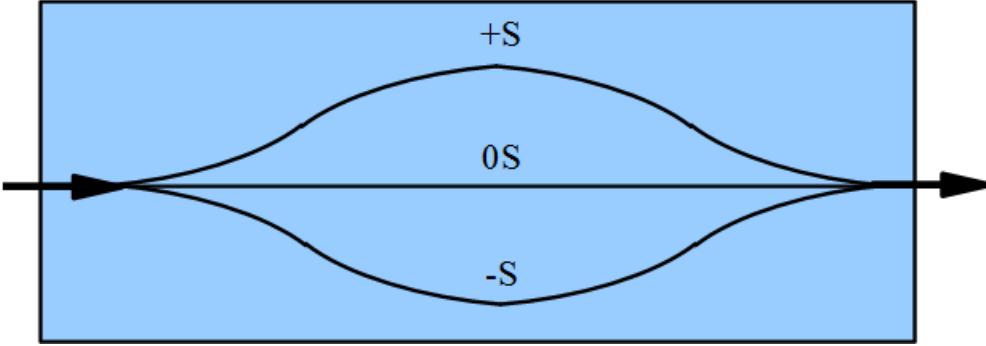


Figure 8: Stern-Gerlach Loop

Ordinarily texts represent the Stern-Gerlach apparatus as separating particles into spin eigenstates denoted by, say, $+S, 0S, -S$. But as in our other examples, the apparatus does not project the particles to eigenstates. Instead it creates a superposition state so that with a detector in a certain position, then as the detector causes the collapse to a spin eigenstate, the detector will only see particles of one spin state. Alternatively if the collapse is caused by placing blocking masks over two of the beams, then the particles in the third beam will all be those that have collapsed to the same eigenstate. It is the detectors or blockers that cause the collapse or projection to eigenstates, not the prior separation apparatus.

We previously saw how a polarization analyzer, contrary to the statement in many texts, does not lose the polarization information of the incident beam when it "separates" the beam (into a positionally-tagged superposition state). In the context of the Stern-Gerlach apparatus, Feynman similarly remarks:

"Some people would say that in the filtering by T we have 'lost the information' about the previous state ($+S$) because we have 'disturbed' the atoms when we separated them into three beams in the apparatus T. But that is not true. The past information is not lost by the *separation* into three beams, but by the *blocking masks* that are put in...."

[2, p. 5-9 (italics in original)]

6 The Separation Fallacy

We have seen the same fallacy of interpretation in two-slit experiments, which-way interferometer experiments, polarization analyzers, and Stern-Gerlach experiments. The common element in all the cases is that there is some 'separation' apparatus that puts a particle into a certain superposition of eigenstates in such a manner that when an appropriately positioned detector induces a collapse to an eigenstate, then the detector will only register one of the eigenstates. The separation fallacy is that this is misinterpreted as showing that the particle was already in that eigenstate in that position as a result of the previous 'separation.' The quantum erasers are elaborated versions of these simpler experiments, and a similar separation fallacy arises in that context.

7 One photon quantum eraser experiment

A simple quantum eraser can be devised using a single beam of photons as in [5]. We start with the standard two-slit setup.

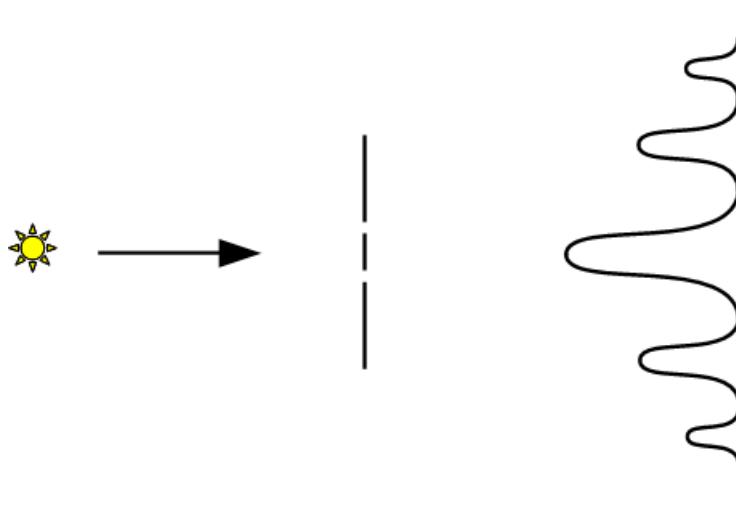


Figure 9: Two-slit setup

After the two slits, a photon could be schematically represented as being in a superposition state $|s1\rangle + |s2\rangle$ (where $s1$ and $s2$ stand for the two slits) which evolves with interference to give the familiar pattern on the far wall.

Then a horizontal polarizer is place in front of slit 1 and a vertical polarizer in front of slit 2.

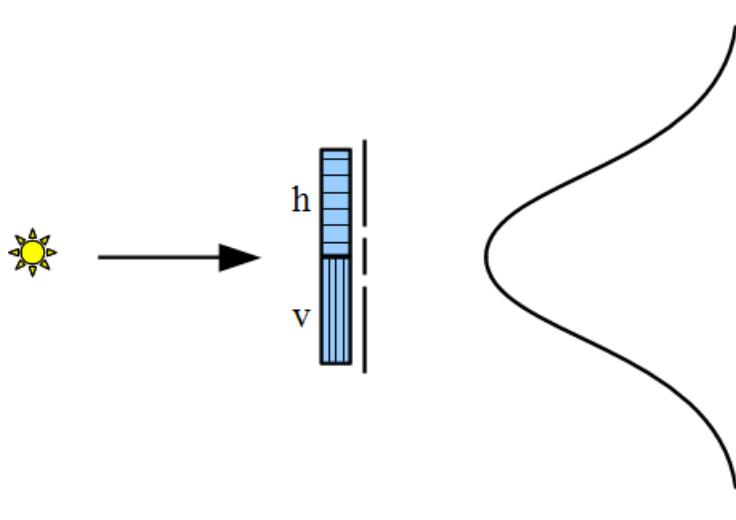


Figure 10: Two-slit setup with v, h polarizers

After the two slits, a photon is in a state that entangles the spatial slit states and the polarization states which might be represented as: $|s1\rangle \otimes |h\rangle + |s2\rangle \otimes |v\rangle$ (for a discussion of this type of entanglement, see [7]). But as this superposition evolves, it cannot be separated into a superposition of the slit-states as before, so the interference disappears.

Then a $+45^\circ$ polarizer is inserted between the two-slit screen and the wall. This transforms the evolving state to:

$$|s1\rangle \otimes |45^\circ\rangle + |s2\rangle \otimes |45^\circ\rangle = [|s1\rangle + |s2\rangle] \otimes |45^\circ\rangle$$

so that the $|s1\rangle + |s2\rangle$ term will show interference in a "fringe" pattern when the 45° polarized photons hit the wall. If we had inserted a -45° polarizer, then again interference in an "antifringe"

pattern would appear as the -45° polarized photons hit the wall. The sum of the fringe and antifringe patterns gives the no-interference pattern of the previous figure.

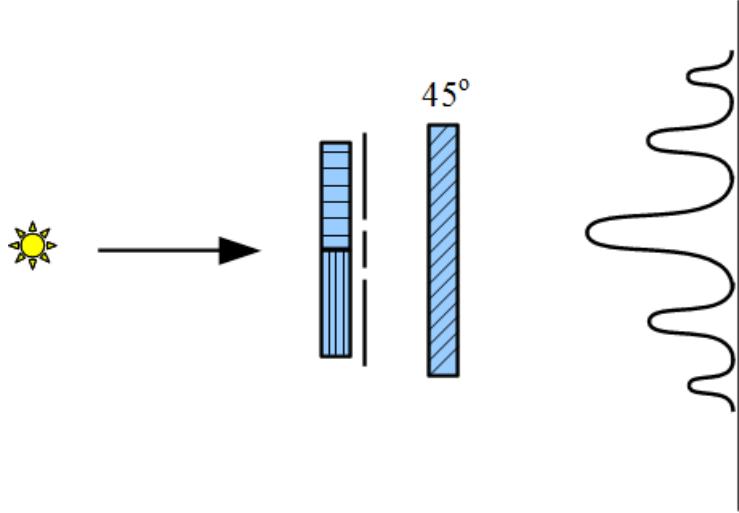


Figure 11: $+45^\circ$ polarizer and fringe pattern

A common description of this type of quantum eraser experiment is that the insertion of the h, v polarizers "marks" the photons with "which-slit information" (Figure 10) that destroys the interference—even if the horizontal or vertical polarization is not measured at the wall. If the horizontal or vertical polarization was measured at the wall, then the evolved superposition state $|s1\rangle \otimes |h\rangle + |s2\rangle \otimes |v\rangle$ would collapse to the evolved version of $|s1\rangle$ (if h was found) or $|s2\rangle$ (if v was found). This is said to reveal the so-called "which-slit information" that the photon went through slit 1 or slit 2, i.e., that at the slits, the photon was already in the state $|s1\rangle$ or $|s2\rangle$ instead of being in the entangled superposition state. By incorrectly inferring that the photon was in one state or the other at the slits—while it would have to "go through both slits" to yield the interference pattern obtained by inserting the 45° polarizer—we seem to be able to retrocause the particle to go through one slit or both slits by withdrawing or inserting the 45° polarizer after a photon has traversed the two slits.

It is precisely the separation fallacy that leads to this inference of retrocausality. In the situation of Figure 10, the photon superposition state $|s1\rangle \otimes |h\rangle + |s2\rangle \otimes |v\rangle$ evolves until it hits the wall. The slit states are indeed marked, tagged, labelled, or entangled with polarization states but this is incorrectly called "which-way information" as if it could "reveal" that the photon was in the state $|s1\rangle$ or $|s2\rangle$ at the slits, i.e., that it went through slit 1 or slit 2.

Also it might be noted that the insertion of a $+45^\circ$ or -45° polarizer does not "restore" the original interference pattern of Figure 9 but picks out the fringe or antifringe interference patterns out of the Figure 10 "mush" of hits.

8 Two photon quantum eraser experiment

We now turn to one of the more elaborate quantum eraser experiments [9].

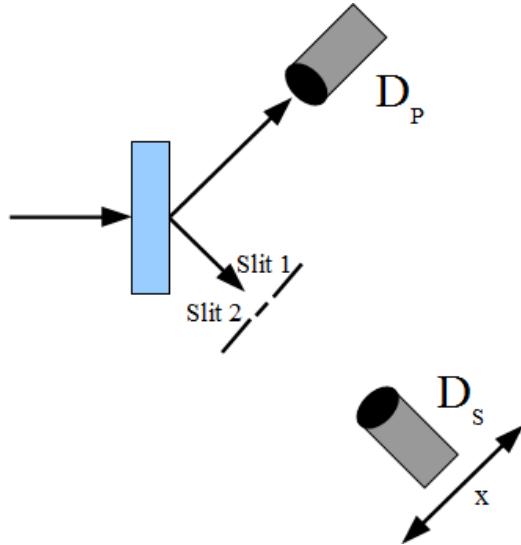


Figure 12: Setup with two slits

A photon hits a down-converter which emits a "signal" p -photon entangled with an "idler" s -photon with a superposition of orthogonal $|x\rangle$ and $|y\rangle$ polarizations so the overall state is:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left[|x\rangle_s \otimes |y\rangle_p + |y\rangle_s \otimes |x\rangle_p \right].$$

The lower s -photon hits a double-slit screen, and will show an interference pattern on the D_s detector as the detector is moved along the x -axis.

Next two quarter-wave plates are inserted before the two-slit screen with the fast axis of the one over slit 1 oriented at $|+45^\circ\rangle$ to the x -axis and the one over the slit 2 with its fast axis oriented at $| -45^\circ\rangle$ to the x -axis.

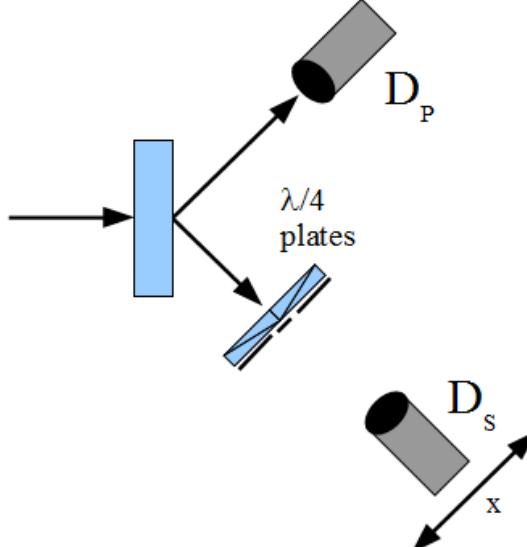


Figure 13: Setup with $\lambda/4$ plates

Then Walborn et al. [9] give the overall state of the system as (where the $s1$ and $s2$ tags refer to the two slits):

$$|\Psi\rangle = \frac{1}{2} \left[\left(|L\rangle_{s1} \otimes |y\rangle_p + i|R\rangle_{s1} \otimes |x\rangle_p \right) + \left(i|R\rangle_{s2} \otimes |y\rangle_p - i|L\rangle_{s2} \otimes |x\rangle_p \right) \right].$$

Then by measuring the linear polarization of the p -photon at D_p and the circular polarization at D_s , "which-slit information" is said to be obtained and no interference pattern recorded at D_s .

For instance measuring $|x\rangle$ at D_p and $|L\rangle$ at D_s imply $s2$, i.e., slit 2. But as previously explained, this does *not* mean that the s -photon went through slit 2. It means we have positioned the two detectors *in polarization space*, say to measure $|x\rangle$ polarization at D_p and $|L\rangle$ polarization at D_s , so only when the superposition state collapses to $|x\rangle$ for the p -photon and $|L\rangle$ for the s -photon do we get a hit at both detectors.

This is the analogue of the one-beam-splitter interferometer where the positioning of the detectors would only record one collapsed state which did not imply the system was all along in that particular arm-eigenstate. The phrase "which-slit" or "which-arm information" is a misnomer in that it implies the system was already in a slit- or way-eigenstate and the so-called measurement only revealed the information. Instead, it is only at the measurement that there is a collapse or projection to an evolved slit-eigenstate (not at the previous separation due to the two slits).

Walborn et al. indulge in the separation fallacy when they discuss what the so-called "which-path information" reveals.

Let us consider the first possibility [detecting p before s]. If photon p is detected with polarization x (say), then we know that photon s has polarization y before hitting the $\lambda/4$ plates and the double slit. By looking at [the above formula for $|\Psi\rangle$], it is clear that detection of photon s (after the double slit) with polarization R is compatible only with the passage of s through slit 1 and polarization L is compatible only with the passage of s through slit 2. This can be verified experimentally. In the usual quantum mechanics language, detection of photon p before photon s has prepared photon s in a certain state. [9, p. 4]

Firstly, the measurement that p has polarization x after the s photon has traversed the $\lambda/4$ plates and two slits [see their Figure 1] does not retrocause the s photon to already have "polarization y before hitting the $\lambda/4$ plates." When photon p is measured with polarization x , then the two particle system is in the superposition state:

$$i|R\rangle_{s1} \otimes |x\rangle_p - i|L\rangle_{s2} \otimes |x\rangle_p = [i|R\rangle_{s1} - i|L\rangle_{s2}] \otimes |x\rangle_p$$

which means that the s photon is *still* in the slit-superposition state: $i|R\rangle_{s1} - i|L\rangle_{s2}$. Then only with the measurement of the circular polarization states L or R at D_s do we have the collapse to (the evolved version of) one of the slit eigenstates $s1$ or $s2$ (in their notation). It is an instance of the separation fallacy to infer "the passage of s through slit 1" or "slit 2", i.e., $s1$ or $s2$, instead of the photon s being in the tagged superposition state $|\Psi\rangle$ after traversing the slits.

Let us take a new polarization space basis of $|+\rangle = +45^\circ$ to the x -axis and $|-\rangle = -45^\circ$ to the x -axis. Then the overall state can be rewritten in terms of this basis as (see original paper for the details):

$$|\Psi\rangle = \frac{1}{2} \left[(|+\rangle_{s1} - i|+\rangle_{s2}) \otimes |+\rangle_p + i(|-\rangle_{s1} + i|-\rangle_{s2}) \otimes |-\rangle_p \right].$$

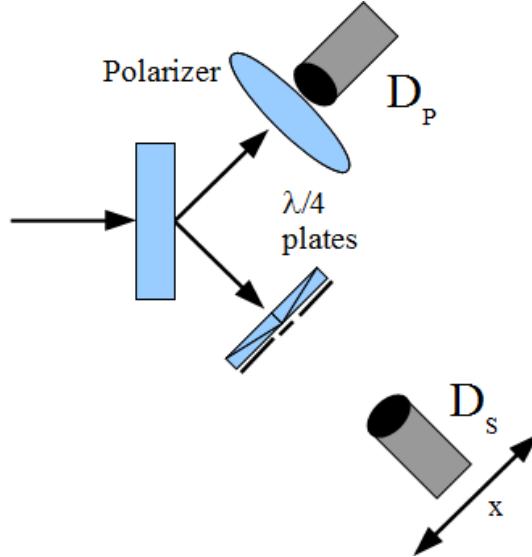


Figure 14: Setup with D_p polarizer

Then a $|+\rangle$ polarizer or a $|-\rangle$ polarizer is inserted in front of D_p to select $|+\rangle_p$ or $|-\rangle_p$ respectively. In the first case, this reduces the overall state $|\Psi\rangle$ to $|+\rangle_{s1} - i|+\rangle_{s2}$ which exhibits an interference pattern, and similarly for the $|-\rangle_p$ selection. This is misleadingly said to "erase" the so-called "which-slit information" so that the interference pattern is restored.

The first thing to notice is that two complementary interferences patterns, called "fringes" and "antifringes," are being selected. Their sum is the no-interference pattern obtained before inserting the polarizer. The polarizer simply selects one of the interference patterns out of the mush of their merged non-interference pattern. Thus instead of "erasing which-slit information," it selects one of two interference patterns out of the both-patterns mush.

Even though the polarizer may be inserted after the s -photon has traversed the two slits, there is no retrocausation of the photon going through both slits or only one slit as previously explained.

One might also notice that the entangled p -photon plays little real role in this setup (as opposed to the "delayed erasure" setup considered next). Instead of inserting the $|+\rangle$ or $|-\rangle$ polarizer in front of D_p , insert it in front of D_s and it would have the same effect of selecting $|+\rangle_{s1} - i|+\rangle_{s2}$ or $|-\rangle_{s1} + i|-\rangle_{s2}$ each of which exhibits interference. Then it is very close to the one-photon eraser experiment of the last section.

9 Delayed quantum eraser

If the upper arm is extended so the D_p detector is triggered last ("delayed erasure"), the same results are obtained. The entangled state is then collapsed at D_s . A coincidence counter (not pictured) is used to correlate the hits at D_s with the hits at D_p for each fixed polarizer setting, and the same interference pattern is obtained.

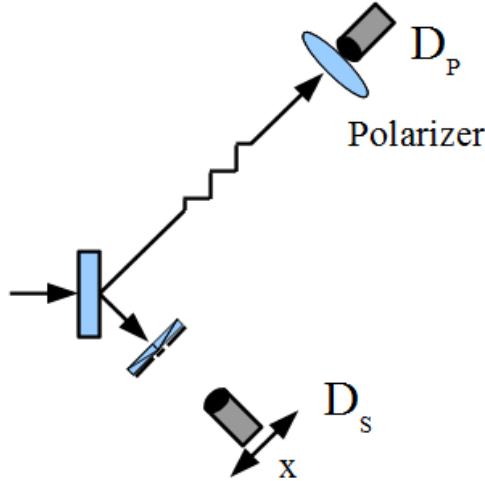


Figure 15: Setup for "delayed erasure"

The interesting point is that the D_p detections could be years after the D_s hits in this delayed erasure setup. If the D_p polarizer is set at $|+\rangle_p$, then out of the mush of hits at D_s obtained years before, the coincidence counter will pick out the ones from $|+\rangle_{s1} - i|+\rangle_{s2}$ which will show interference.

Again, the years-later D_p detections do not retrocause anything at D_s , e.g., do not "erase which-way information" years after the D_s hits are recorded (in spite of the "delayed erasure" talk). They only pick (via the coincidence counter) one or the other interference pattern out of the years-earlier mush of hits at D_s .

"We must conclude, therefore, that the loss of distinguishability is but a side effect, and that the essential feature of quantum erasure is the post-selection of subensembles with maximal fringe visibility." [8, p. 79]

The same sort of analysis could be made of the delayed choice quantum eraser experiment described in the paper by Kim et al. & Scully [6]. Brian Greene [4, pp. 194-199] gives a good informal analysis of the Kim et al. & Scully experiment which avoids the separation fallacy and thus avoids any implication of retrocausality.

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